Thermal insulation potential of non-industrial hemp (Moroccan cannabis sativa L.) fibers for green plaster-based building materials

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Abstract

Hemp, or industrial cannabis, is on a massively growing trend as a natural additive for high-performance bio-based building materials. However, thousands of stems from vernacular cannabis cultivation in developing countries, such as Morocco, are overlooked and regarded as biomass waste used for rural household purposes. The objective of this paper is to assess the potential use of Moroccan cannabis fibers in the manufacture of local bio-insulating plasterboards. Firstly, the study focuses on the mineralogical, morphological, and chemical characterization of used fibers using X-ray diffraction (XRD), thermogavimetric analysis (TGA), scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS). Secondly, the impact of fiber addition on the thermal performance of plaster was experimentally studied using Hot Disk and flash methods. For this study, one hundred local fibro-plasterboards were developed by adding Moroccan Hemp Fibers (MHFs) to local plaster at different weight replacement ratios: 0, 2, 4, and 6% in order to evaluate the effect of fiber content on the thermal insulation quality of plaster and the variation of the thermal capacity of developed bio-composites. The experimental tests demonstrate the effectiveness of Moroccan hemp stems in improving the thermal transport properties of plaster and making it more thermally efficient. The incorporation of 6% in weight of MHFs in plaster matrix considerably reduced the density, enhanced the thermal insulation and slowed the heat transfer rate respectively by 24.5%, 31.3% and 8.5% when compared to plaster without fibers. The addition of 2% in weight of MHFs showed the best results in terms of thermal heat capacity. Finally, to evaluate the energy performance of developed plasterboards at building scale, annual simulations using EnergyPlus for a residential building located in two different semi-arid climates of Morocco were carried out. The results indicate that buildings with 40 mm Moroccan hemp plasterboard (MHP) have a considerable potential to reduce the energy consumption of buildings and provide passive thermal comfort for occupants, especially during summer periods. Therefore, non-industrial hemp is a good candidate for the development of local lightweight low-environmental impact (LLL) construction materials with contributions for building energy efficiency.

Key-words

Bio-based building material, energy efficiency, non-industrial hemp, passive cooling, simulation, thermal insulation.

Highlights

- Vernacular hemp fibers are used as partial bio-aggregate replacement in plasterboards.
- Physical, mineralogical and chemical analyses of Moroccan hemp fibers are carried out.
- Local bio-sourced plasterboards were developed for roof thermal insulation upgrading.
- Non-industrial hemp substantially improves the thermal transport properties of plaster.
- The simulation of a residential building confirmed the effectiveness of Moroccan hemp plaster in passive cooling.

Nomenclature

a	Thermal diffusivity [$mm^2.s^{-1}$]
CI	Crystallinity Index
c_p	Specific heat capacity [$J.kg^{-1}.K^{-1}$]
e	Thickness [m]
h_i	Heat transfer coefficient of internal surfaces [$W.m^{-2}.K^{-1}$]
h_e	Heat transfer coefficient of external surfaces [$W.m^{-2}.K^{-1}$]
R_j	Thermal resistance of the jth layer [$m^2.K.W^{-1}$]
G-value	Solar factor of glass
U-value	Thermal transmittance [$W.m^{-2}.K^{-1}$]
%Cr	Percentage crystallinity [%]

Greek Symbols

λ	Thermal conductivity [$W.m^{-2}.K^{-1}$]

Acronyms

AMEE	Agence Marocaine pour l'Efficacité Energétique
ASHRAE	American Society of Heating, Refrigerating and Air-conditioning Engineers
HTC	Δ^9-Tetrahydrocannabinol
MHF	Moroccan Hemp Fiber
MHP	Moroccan Hemp Plasterboard
RTCM	Règlement Thermique de Construction au Maroc
TMY	Typical Meteorological Year
UNODC	United Nations Office on Drugs and Crime

1 Introduction

Local bio-composites for building applications are one of the major and most promising solutions to reduce the total carbon footprint of buildings and construction sectors along the chain from cultivation to the manufacturing process (Hayat et al., 2020). Over the last decades, plant-based aggregates derived from the stem of plants have attracted widespread interest due to their application in lightweight low-cost building materials (Amziane and Collet, 2017). Moreover, they represent renewable resources that are easy-to-use with conventional binders such as cement, clay and plaster. For example, Soltan et al. (Soltan et al., 2017) studied the thermo-mechanical properties of a fiber-cement composite reinforced with Curauá fibers and they have shown that the incorporation of Curauá fibers in cementitious materials could be effective for the development of lightweight thermal insulation materials, and even compete with synthetic fibers with a tensile strength of the order of 620 MPa . Recently, Ouedraogo et al. (Ouedraogo et al., 2019) studied the thermo-mechanical effect of the addition of fonio straw fibers to a local clay matrix for adobe stabilization purposes. As expected, the results show that a small amount addition of plant fibers improves the mechanical properties of adobes and decreases their thermal conductivity by 67 % using 1 % in weight of fonio fibers. In addition, Iucolano et al. (Iucolano et al., 2015) investigated the mechanical behaviours of a fiber/plaster mixture using abaca fibers. It was observed that the use of 2 % in weight of treated abaca fibers with distilled water could be efficient for the manufacture of bio-sourced gypsum-based composites with enhanced mechanical characteristics.

Hemp or the industrial form of cannabis (*Cannabis Sativa L.*) plant is the most used additive among researchers working on next generation building materials and R&D construction projects (Abu-Jdayil et al., 2019). Indeed, hemp possesses interesting features, mainly its high cellulose content (Jones and Brischke, 2017; Thygesen et al., 2011), its high hygrothermal efficiency (Oumeziane et al., 2020) and its carbon storage capacity (Pervaiz et al., 2003). These interesting properties have led to an immense increase in the number of hemp industry companies throughout the world, including both cultivation and processing. Besides, a considerable amount of literature has been published on hemp as an alternative material for low-carbon building applications (Ingrao et al., 2015) and others (Ranalli and Venturi, 2004; Salentijn et al., 2015). To develop green hemp-based building materials with optimal properties, different tests were performed using treated/untreated hemp compounds such as fibers (Gregoire et al., 2019), which represent the outside part of the stem and shives (Bourdot et al., 2017) or hurds (Nguyen et al., 2009), which compose the inner woody part of hemp. In the literature, hemp-lime mix, often referred to as "*HempCrete*", is the most well-known hemp-based composite that has proven its effectiveness in enhancing the thermal comfort performance of buildings. Recently, Jami et al. (Jami et al., 2019) examined the state-of-the-art of hemp concrete and reviewed its various properties and application in building construction. The review shows that the incorporation of hemp in concrete leads to design thermally efficient masonry units with a thermal conductivity ranging from 0.06 to 0.18 W/m.K. Furthermore, this kind of plant-derived aggregate has been tested with several natural and synthetic binders. For example, Mazhoud et al. (Mazhoud et al., 2018) studied a hemp-clay composite and compared its hygrothermal performance with that of hemp-lime concrete, highlighting the positive effect of hemp addition on the thermal performance of clayey matrices. The study reported that the incorporation of hemp improves the thermal insulation quality as well as the moisture buffering ability of clays more than lime-based binders. Iucolano et al. (Iucolano et al., 2019) compared the effect of hemp on the mechanical performance of gypsum board composites with that of glass fibers, emphasizing the competitiveness of hemp. More recently, Boccarusso et al. (Boccarusso et al., 2020) investigated the mechanical response of bio-based gypsum boards reinforced with hemp fabrics. The authors demonstrated the effective use of fabrics compared to short fibers on the mechanical behaviour of plasterboard, reaching a good flexural strength of 6.74 MPa.

All these research works have been focused on studying the effect of hemp content of the mechanical characteristics of plaster without considering the resulting thermal performance rate. Moreover, few plant fibers have been tested as building additives in plaster binders (Ashour et al., 2010; Dalmay et al., 2010; Hamza et al., 2013; Iucolano et al., 2018; Liuzzi et al., 2018), compared to cement and clay, showing encouraging results in terms of both mechanical and thermal insulation properties. Further studies thus are needed using new country-specific plant fibers in order to design local-appropriate building materials.

In this paper and as a first attempt, a local plaster-based composite using non-industrial hemp from Morocco was developed and characterized. So far there is only one article in the literature partially dealing with Moroccan cannabis stalks for building application purposes, which was recently published by Brümmer et al. (Brümmer et al., 2018). The authors compared the impact of Spanish industrial and Moroccan vernacular hemp fibers treated with water on the mechanical performance of hemp-clay composites, showing the feasibility of the use of Moroccan hemp in building material manufacturing.

The originality of this present work is the development of one hundred percent local hemp-plasterboards for building retrofit applications (false ceiling, etc.) using vernacular hemp fibers collected from Northern Morocco. This work is also significant as the finding results will participate in the legalization of cannabis cultivation and creating local jobs. Density, thermal transport properties of prepared Moroccan Hemp-Plasterboards (MHP) were determined using the Hot Disk and the boxes methods. The heat thermal capacity of studied composites was discussed. Then, building thermodynamic simulations of a residential building located in two different semi-arid climates were carried out in order to evaluate the potential use of MHP boards for passive cooling and reducing the annual energy consumption in buildings.

Overview of Moroccan hemp

The cultivation of cannabis in Morocco began in the late sixteenth century, only in small areas of Ketama and Bab Berred located in Moroccan Rif Mountains (Potter et al., 2013). This crop has been extended from 40 km^2 to reach almost all provinces of northern Morocco covering a total surface area of about 125 000 hectares in 2003 (Bellakhdar, 2013), as presented in Fig. 1. According to (UNODC., 2003), Chefchaouen (50%), Taounate (19%) and Al Houceima (17%) are the three main provinces of Cannabis cultivation in Morocco.

The Moroccan cannabis is of type *Cannabis Sativa L. var. indica* which is the non-industrial form of hemp grown for its leaves characterized by a high content of Δ^9 -tetrahydrocannabinol (THC). For this reason, much of the available literature deals with the cannabis resin production (Chouvy and Afsahi, 2014), as well as the psychotropic properties (Afsahi, 2017; Merzouki et al., 2008) of Moroccan hemp. *Kif* is the commonly used word to denote the worldwide well-known Moroccan cannabis powder derived from flowers and leaves of cannabis, from which several products are made, such as *Hashish* (Chouvy and Afsahi, 2014). However, tons of Moroccan hemp stalks are considered as a biomass-waste practically used for rural domestic purposes, despite their great interest in building construction as discussed in (Brümmer et al., 2018). Therefore, this paper is targeted to valorize the use of MHFs in the manufacture of local building materials by investigating the thermal performance of non-industrial hemp plaster-based composites.

Moreover, the medical nature of the Moroccan cannabis plant due to its relatively high THC contents has led the Moroccan Government to enact punitive policies towards local farmers, which have negatively affected cannabis cultivation with a reduction of 65% from 2003 to 2011 (Chouvy and Afsahi, 2014). To promote the cannabis cultivation in Morocco and ensure its leadership position in the global market, Chouvy et al. (Chouvy and Macfarlane, 2018) discussed some modern agricultural practices related to cannabis industry. In this respect, this work also contributes to the promotion and legalization of cannabis for industrial purposes by developing new building materials based on Moroccan cannabis fibres as a strategy to create local green jobs in the construction sector.

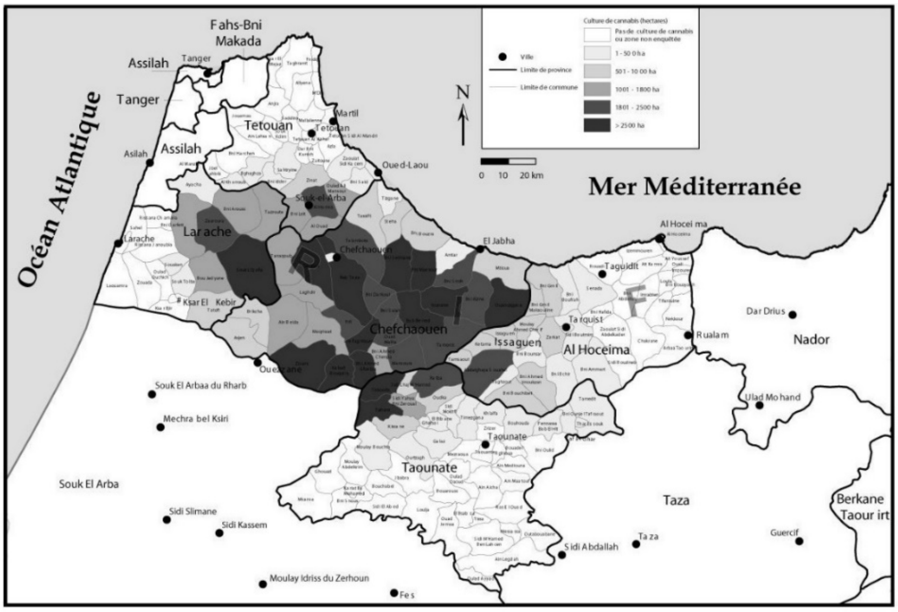


Fig. 1 Cannabis cultivation in Northern Morocco in 2004 (Potter et al., 2013)

2 Materials and samples

2.1 Used hemp fibers

The hemp stems (Fig. 2a) coming from the northern Rif mountains region of Morocco were used in this study to develop country-specific hemp-plaster composites. The full hemp stalks were cut manually into10-20 mm length to ensure a homogeneous mixture, as shown in Fig. 2b.

Unlike industrial hemp, there is a lack of information about the mineralogical and the chemical composition of MHFs, which is needed in quantifying the cellulose portion and understanding the difference between ancestral and industrial hemp fibers, particularly with regard to the manufacture of building materials. Isahq et al. (Isahq et al., 2015) investigated the chemical composition of leaves, seeds and stems of *Cannabis var. indica* located in Pakistan, while Singha et al. (Singha and Rana, 2012) and Buitrago-Suescún et al. (Buitrago-Suescún and Monroy, 2018) studied the mineralogical composition of *Cannabis indica* fibers, collected respectively from Himalayan and Colombian regions. Table 1 summarizes the obtained results.

As the composition changes from place to place, and to compare the finding results with those listed in Table 1, mineralogical and thermochemical tests are carried out on the used fibers in order to identify the characteristics of Moroccan hemp stems. Details of these experimental analyses were discussed in the Methods section.

Fig. 2 Moroccan hemp: (a) stalks (b) fibers used during the sample preparation

Table. 1. Properties of Cannabis *Sativa L. var. indica* (Buitrago-Suescún and Monroy, 2018; Isahq et al., 2015; Singha and Rana, 2012)

Property	Value
Crystallinity (%)	67.07
Crystallinity Index	0.509
Sodium (ppm)	3.83
Potassium (ppm)	6.58
Iron (ppm)	7.51
Magnesium (ppm)	0.88
Phosphorus (ppm)	2.67
Calcium (ppm)	2.24
Zinc (ppm)	1.89
Cooper (ppm)	1.24
Cellulose (%)	68 - 69
Hemicellulose (%)	4.4
Lignin (%)	14
Nitrogen (%)	0.98
Moisture (%)	14.5
Ash (%)	2.59

2.2 Binder

In order to develop a one hundred percent local building material, a commercial plaster product provided from a local company located in eastern Morocco was used in this work. The microstructure of used plaster was carried out by scanning electron microscopy. The SEM image (Fig. 3) shows that our plaster consists of both crystal forms of α- and β-hemihydrates. This plaster contains a high content of hydrated β-hemihydrate due to the calcination process of calcium sulphate (Singh et al., 2007), highlighting the good quality of the used matrix for building applications. The main chemical composition of Moroccan plaster are listed in Table 2. The SEM-EDS analysis was also conducted to identify the surface elemental composition of the used plaster (Fig. 4). The obtained results are in a good agreement with those obtained by X-ray fluorescence spectroscopy.

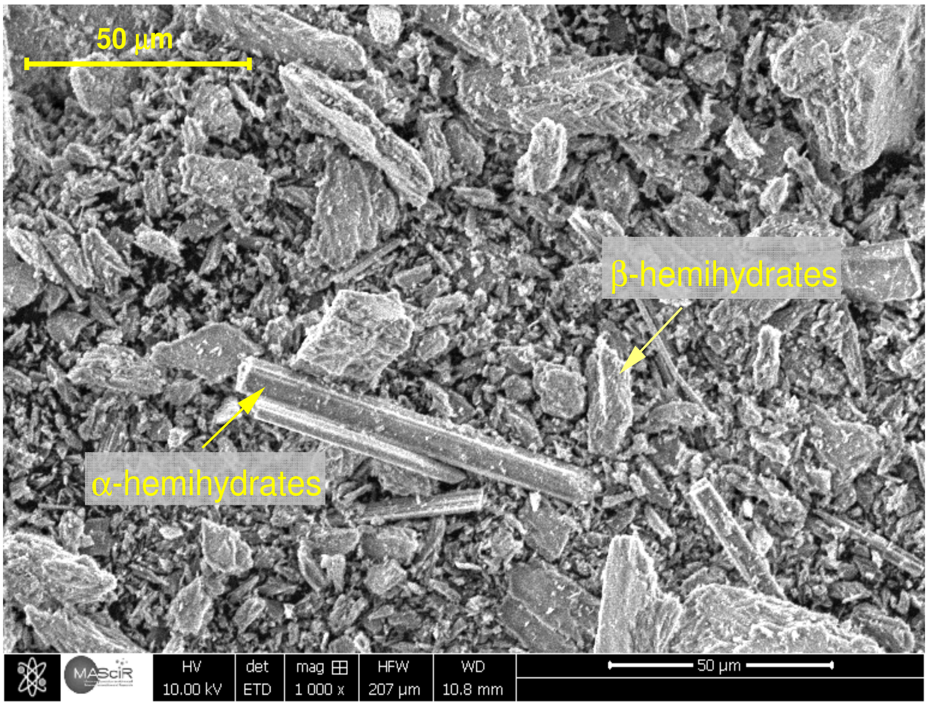
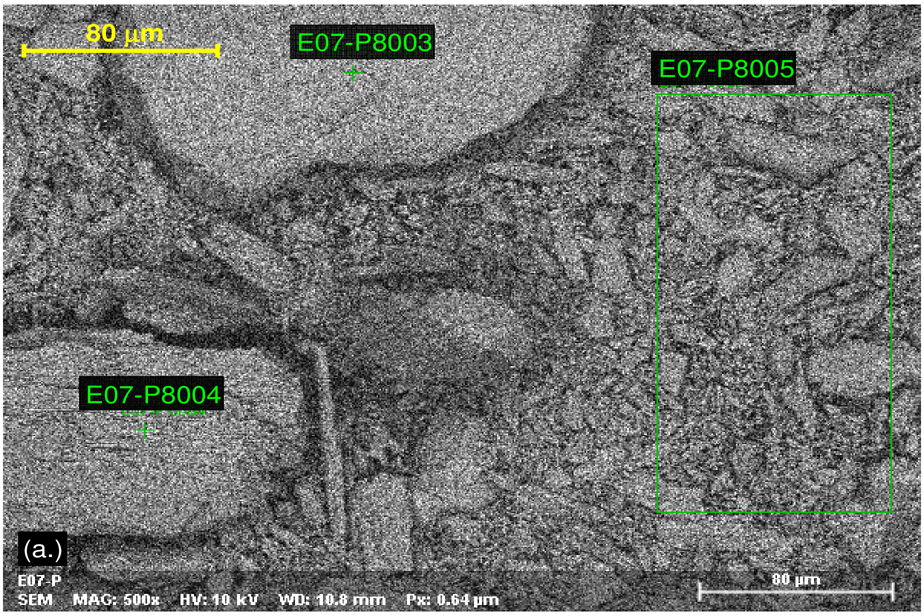


Fig. 3 SEM micrograph of used plaster



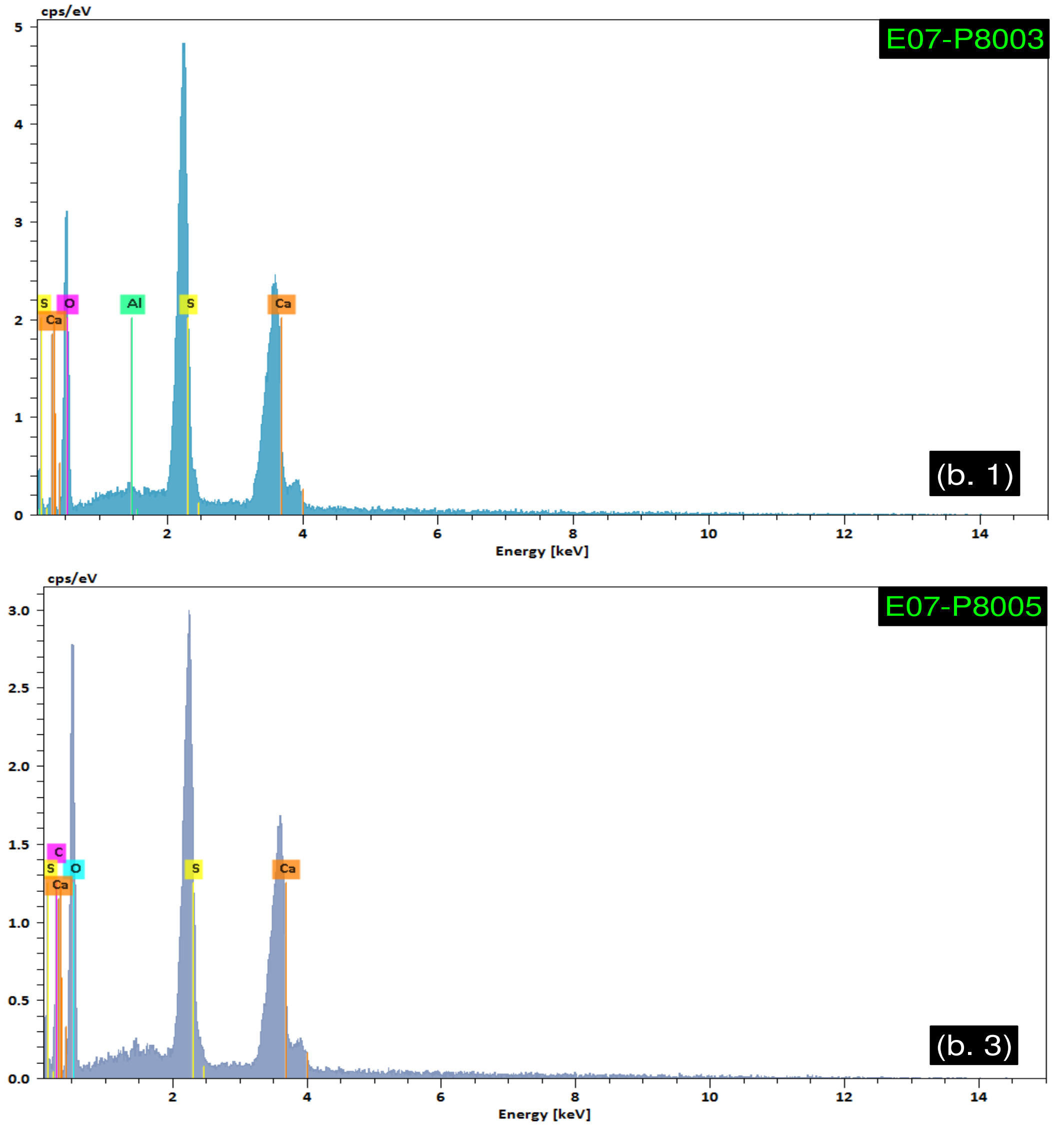


Fig. 4 SEM-EDS results of used plaster: (a) SEM image (b) EDS of three different spectra

Table 2. Properties of plaster

Composition (%)	Moroccan plaster		Used plaster
	Chemical composition (XRF)		Surface chemical composition (SEM-EDS)
	(Ouakarrouch et al., 2020)	(Lakrafli et al., 2012)	Our work
SO_3	43.23	48.23	20.23
CaO	33.19	37	8.3
SiO_2	0.68	1.34	-
MgO	0.48	1.22	0.08
AL_2O_3	0.11	0.47	-
Na_2O	0.09	0.17	-
Fe_2O_3	0.08	0.22	-

2.3 Preparation of samples

The samples were prepared at room temperature by dry mixing the Moroccan hemp fibers (MHFs) with local gypsum plaster for 2 min before adding the required water for compaction. The fibers were cut manually (maximum length 20 mm) as shown in Fig. 2b. Then, and after one minute of wet mixing, the mixture was distributed homogeneously into a 150×150×20 mm^3 aluminium mould and lightly pressed to avoid air cavities. Subsequently, the mould was lifted rapidly and carefully due to the fast-hardening property of plaster. For each specimen, the mould was properly pre-lubricated and placed on flat and moist surfaces to prevent adhesion when removing the mould and to ensure smooth surface of frames.

In contrast to several studies on plaster-based composites (Lachheb et al., 2019; Zhang et al., 2018), a water-to-plaster ratio (w/p) of 0.5 was chosen here for water-saving purposes. Different mass fractions of MHFs were used (0%, 2%, 4% and 6%) to evaluate the effect of Moroccan hemp fibers on the thermal performance of plaster for roof/ceiling applications. The 6% in weight of MHFs represents the maximum rate that can be incorporated in plaster due to the loss of plaster compaction. The detailed mix composition of the prepared hemp-plasterboards is reported in Table 3. A total of four different sets of samples were prepared, involving the reference case that represents plaster samples without fiber addition. The front views of MHP composites are presented in Fig. 5. Considering the composite heterogeneity, other cylindrical specimens with dimensions 50 x 20 mm^2 were manufactured adopting the same protocol. In total, ten specimens for each mixture were characterized (8 rectangular + 2 cylindrical). For thermal testing purposes, all samples were cured at air room temperature for 48 h. afterwards, they were dried to constant mass in an oven at 50 °C to constant mass and weighted each 8 hours until the difference between two successive weights did not exceed 1g. The specimens were then sealed in leak-proof plastic bags and transported for thermal characterization.

Table 3. Mix proportions of studied composites (%)

Mixture code	Plaster	W/P ratio	Fiber content
MHP0	100	0.5	0
MHP2	98	0.5	2
MHP4	96	0.5	4
MHP6	94	0.5	6

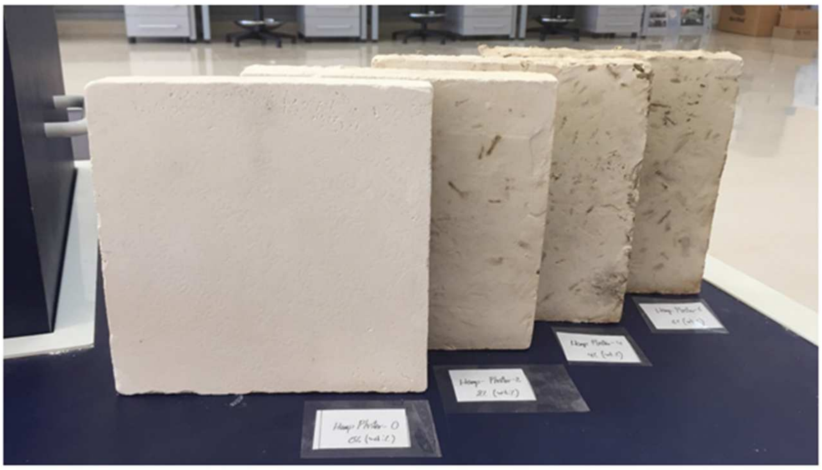


Fig. 5 Image of prepared MHP composites

3 Methods

3.1 Mineralogical, physical and chemical characterization of used fibers

The X-ray diffraction (XRD) analysis of the hemp stem powder was carried out on a SHIMADZU XRD-6000 diffractometer (λ = 0.154 nm, Cu-Kα radiation) to identify the mineralogy and the crystallinity index of the used fibers. The samples were scanned at a scan rate of 2 deg.min^{-1} from 5° to 37° at 2θ scale.

The Thermal Gravimetric Analysis (TGA) was performed in a DTG-60 Shimadzu simultaneous TG/DTA apparatus to study the thermal decomposition of Moroccan hemp fibers under air atmosphere using powdery samples of 6.5 mg. The fibers were heated from 30 to 750 °C at a constant heating rate of 10 °C.min^{-1}.

The microstructure of MHFs was studied using Scanning Electron Microscopy with a field emission scanning electron microscope (SEM; FEI, FEG-450). The surface element composition of the fibers was also characterized by Energy-Dispersive Spectroscopy (EDS; Bruker, XFlash 6/30).

3.2 Hot disk method

A simultaneous identification of thermal transport properties of developed composites, including the thermal conductivity, thermal diffusivity and volumetric heat capacity, was carried out by means of a TPS 2200 (Hot Disk Inc., Sweden) apparatus. This method is based on a Transient Plane Source (TPS) technique, which consists in studying the rapid transient response of samples according to ISO 22007-2 standard (22007-2, 2008). The measurement protocol relies upon monitoring the time-dependent temperature evolution through the samples via a double spiral sensor, which serves as both an electrical heater and a temperature-sensing element. Firstly, the hot disk sensor is sandwiched between two identical specimens, as shown in Fig. 6. Secondly, and after thermal stabilization for up to 15 minutes of contact, the specimens are heated through the sensor with a direct electrical current. Then, the thermal transport properties are determined based on the recorded temperature increase. The theoretical framework as well as the governing equations of the hot disk method are detailed in (Gustafsson, 1991; Mihiretie et al., 2017).

The test measurements were carried out under ambient room conditions (28 °C ± 1 °C) with a Kapton sensor Ref. 5501 of 6.403 mm radius, an electrical power between 0.08 and 0.12 W, and a measurement time of 80 seconds. The numerical results were interpreted by using hot disk thermal analyser v 7.3 software.

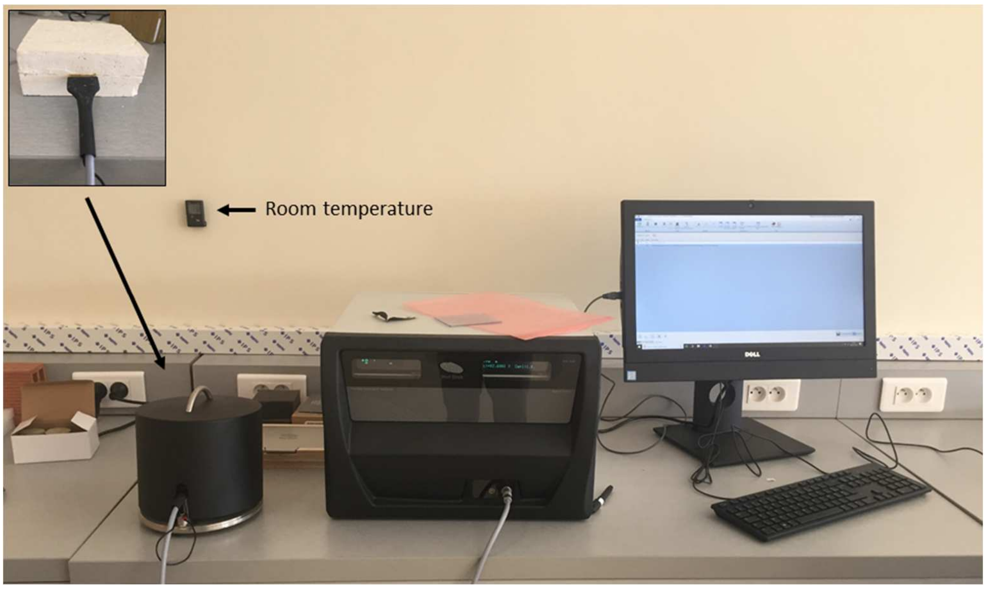


Fig. 6 Experimental setup of hot disk method

3.3 Flash method

The motive behind using the flash method is to visualize the real-time temperature increase of the different hemp-plasterboard composites. As thermal diffusivity was already determined by the Hot Disk method, the flash method was used to compare the thermal response of MHP composites under temperature excitation. Contrary to the conventional use of the flash method in estimating the thermal diffusivity property of solid specimens, this test was carried out in order to explain the thermal heat capacity variation of the developed hemp-plasterboard samples. The measurements were performed using the second box of the EI702 cell, which represents the latest version of the boxes method developed and manufactured in Claude Bernard Lyon I University (Menguy et al., 1986). The apparatus relies on a heat pulse thermal diffusivity technique, which is equipped with an incandescent lamp of 1000W and a thermocouple placed on the upper side of the studied sample, as presented in Fig. 7. The underside of the sample is heated with the 1000W lamp for a duration of 25 seconds, and the temperature increase of the upper side is recorded as a function of time. For thermal diffusivity characterization, the measurement principle is based on inverse parameter estimation using partial time interpretation of the upper-surface response curve (i.e. thermogram). According to Degiovanni et al. (Degiovanni and Laurent, 1986), three values of thermal diffusivity are estimated, taking into account heat losses, as follows:

$$a_1 = (e^2 / (t_{5/6})^2)\,(1.150\, t_{5/6} - 1.250\, t_{2/3})$$
$$a_2 = (e^2 / (t_{5/6})^2)\,(0.761\, t_{5/6} - 1.926\, t_{1/2}) \qquad \text{(Eq. 1)}$$
$$a_3 = (e^2 / (t_{5/6})^2)\,(0.618\, t_{5/6} - 0.862\, t_{1/3})$$

Where e is the thickness of the sample, t_i (i = 1/3, 1/2, 2/3, 5/6) is the ith characteristic time when the temperature reaches i of the maximum temperature. The thermal diffusivity of studied samples is then given, within an accuracy of 5%, as the average of the above-mentioned values:

$$a = (1/3) \sum a_i = (a_1 + a_2 + a_3) / 3 \qquad \text{(Eq. 2)}$$

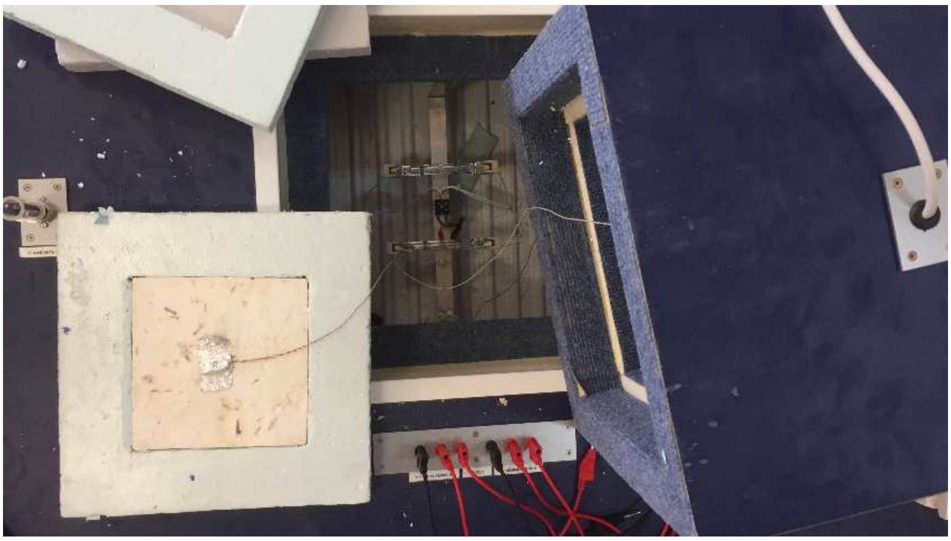


Fig. 7 Experimental setup of flash method

4 Test results and discussion

4.1 Characterization of the fibers

The X-ray diffraction pattern of Moroccan hemp stems is shown in Fig. 8. This analysis was performed to obtain qualitative information on the cellulose content, which is a main criterion for evaluating the effectiveness of bio-fibers in the manufacture of thermal insulation materials with a good mechanical resistance (Jones and Brischke, 2017; Thygesen et al., 2011). The XRD pattern shows the usual main peaks of native cellulose around 15°, 22° and 35° of 2θ scale, representing respectively (110), (002) and (004) lattice planes indicating the presence of type-I cellulose (Segal et al., 1959; Sisti et al., 2016). For crystallinity comparison, the percentage of crystallinity (%Cr) and the empirical crystallinity index (C.I) were calculated using the following equations (Singha and Rana, 2012):

$$\%Cr_{XRD} = I_{200} / (I_{200} + I_{AM}) \times 100 \qquad \text{(Eq. 3)}$$

$$CI_{XRD} = (I_{200} + I_{AM}) / I_{200} \qquad \text{(Eq. 4)}$$

Where I_{AM} is the amorphous phase of cellulose corresponding to the minimum intensity between 18° and 19° of 2θ scale, I_{002} is the maximum intensity of the crystalline peak of the X-ray spectra, as discussed in (Buschle-Diller and Zeronian, 1992).

The results show that the crystallinity index was found to be 0.394 and the percentage of crystallinity was 62.25 %, highlighting the potential use of Moroccan hemp fibers in improving the thermal and mechanical properties of building materials due to the microporous structure and the good cellulose content, respectively (Amziane et al., 2013; Thygesen et al., 2011). The difference between the results obtained and those previously reported, in Table 1, is explained by the originality of the fibers, which includes soil properties and climatic conditions.

The thermal behaviour of the Moroccan hemp fibers is presented in Fig. 9. The TGA curve shows that Moroccan hemp stems were subjected to a quasi-total pyrolysis of 94.8%. Four main weight losses were observed. The first weight loss (8.83%) occurred around 80 °C, corresponding to the removal of physically adsorbed water. The second low-temperature weight loss (64.4%) occurred around 290 °C depicting the rapid decomposition of hemicellulose (Ouajai et al., 2005) and the cleavage of glycosidic cellulose bonds (Rokicki and Kuran; Singha et al., 2012). A third major peak (20.87%) at 427 °C corresponding likely to the oxidation decomposition of the product of stage II, as reported in (Singha et al., 2012). The last small peak (mass loss 0.7%) occurred at 670 °C is due to lignin degradation, which characterized by a lent decomposition at a high temperature (Ouajai et al., 2005). The obtained results are in close agreement with literature data (Ouajai et al., 2005; Rokicki and Kuran; Singha et al., 2012).

The morphologies of Moroccan hemp fibers were observed by SEM analysis. Fig. 10 displays the SEM micrographs of used fibers. We noticed that the microstructure of both Moroccan and industrial hemp is quite similar (Stevulova et al., 2018). SEM images show that Moroccan hemp contains micro-pores, which efficiently enhance the thermal insulation of building materials.

For the chemical composition, the coupled SEM-EDS analysis was performed to investigate the main elementary composition of used fibers, as shown in Fig. 11. The EDS spectrums show that the Moroccan hemp stems contained mainly potassium, calcium and magnesium. As listed in Table 1, a high content of potassium as Pakistan cannabis fibers was observed. However, Moroccan hemp stems exhibited a higher content of magnesium and calcium, while it composed of small amounts of phosphorous. This difference in chemical composition of cannabis fibers is likely due to site-specific cultivation characteristics. Further studies are needed to study the effect of chemical composition on thermal performance of hemp-based building materials. Table 4 summarizes the obtained results of previous analyses on Moroccan hemp stems. Elemental composition of MHFs was given as the average value of EDS spectrums.

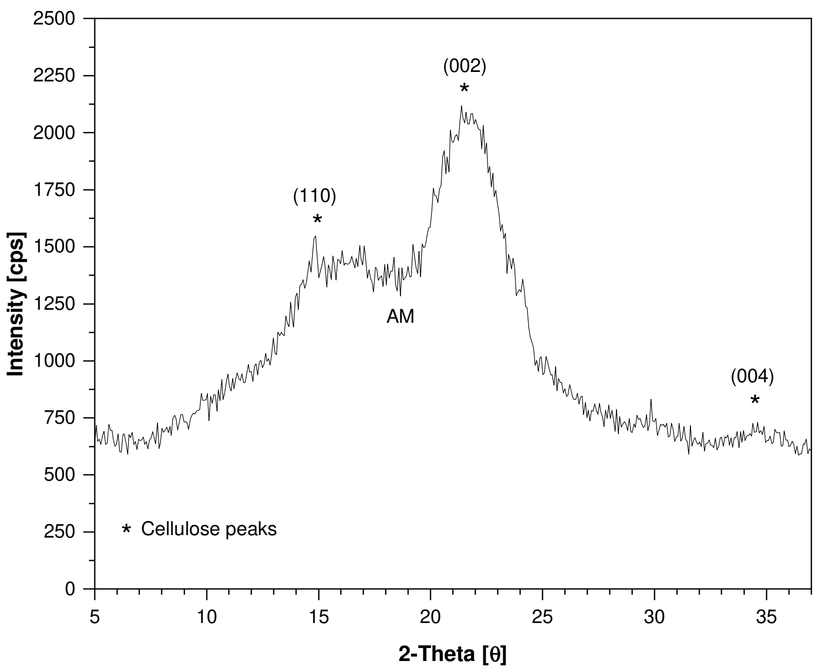


Fig. 8 XRD pattern of MHFs

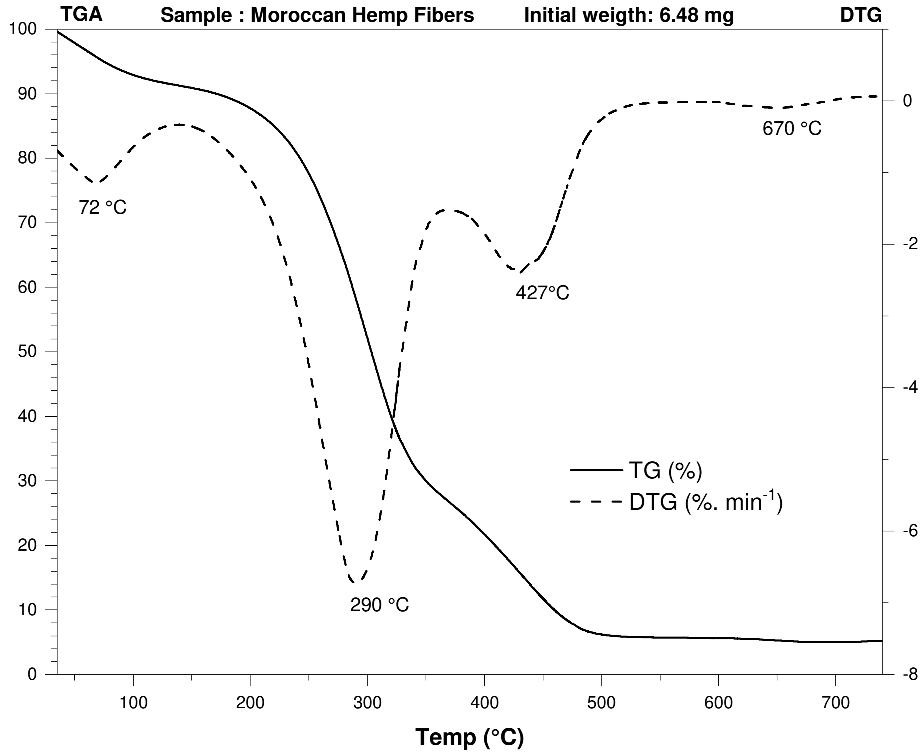
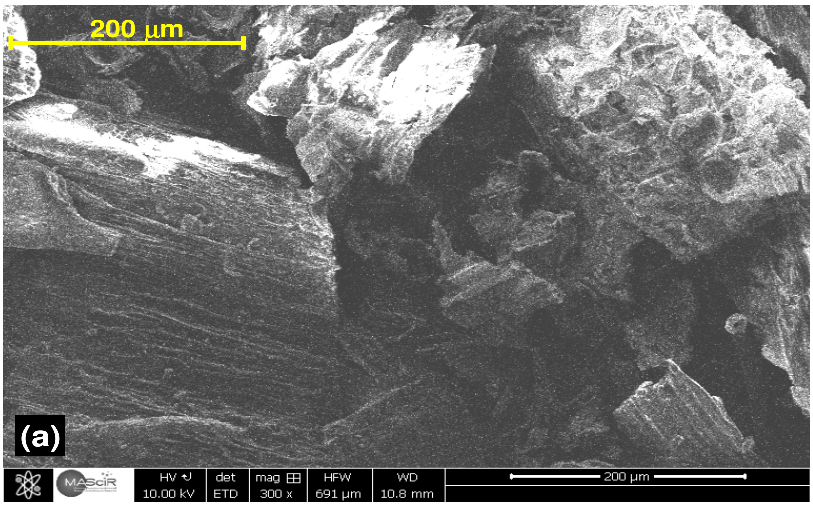
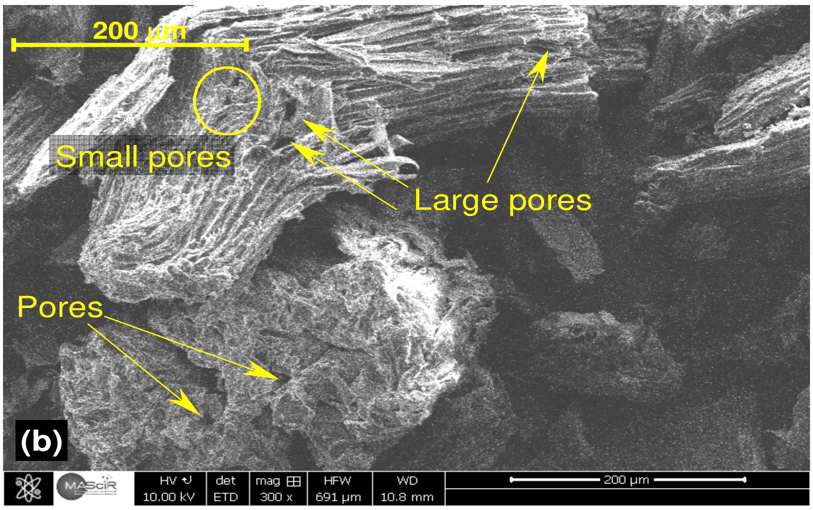


Fig. 9 TG-DTG pattern of MHFs





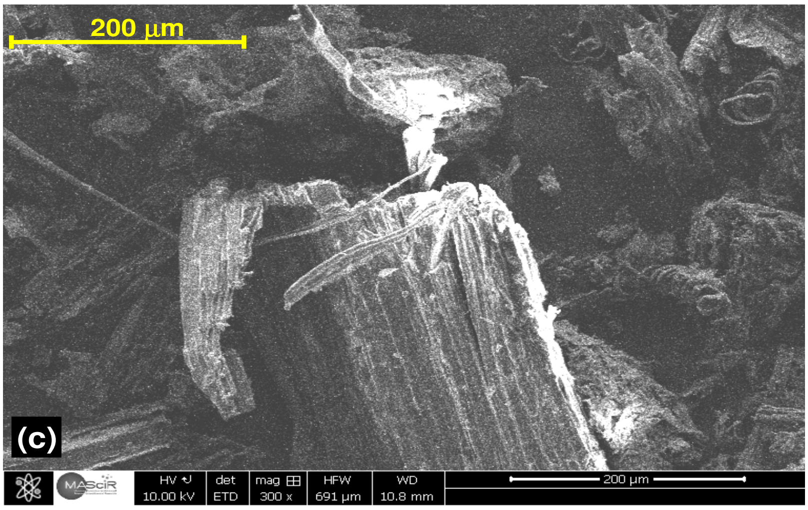
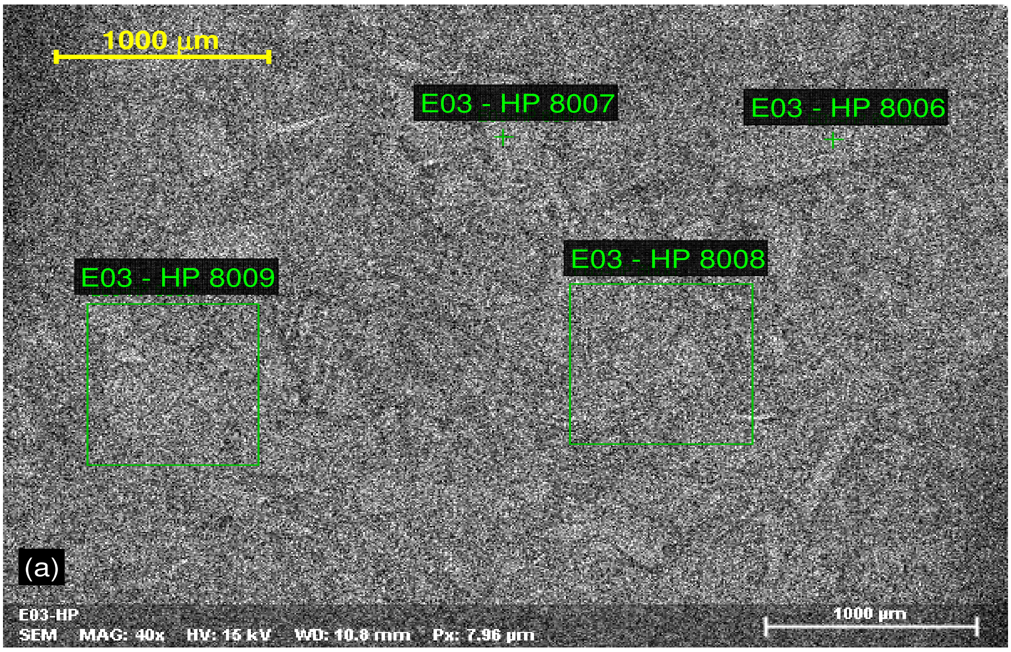
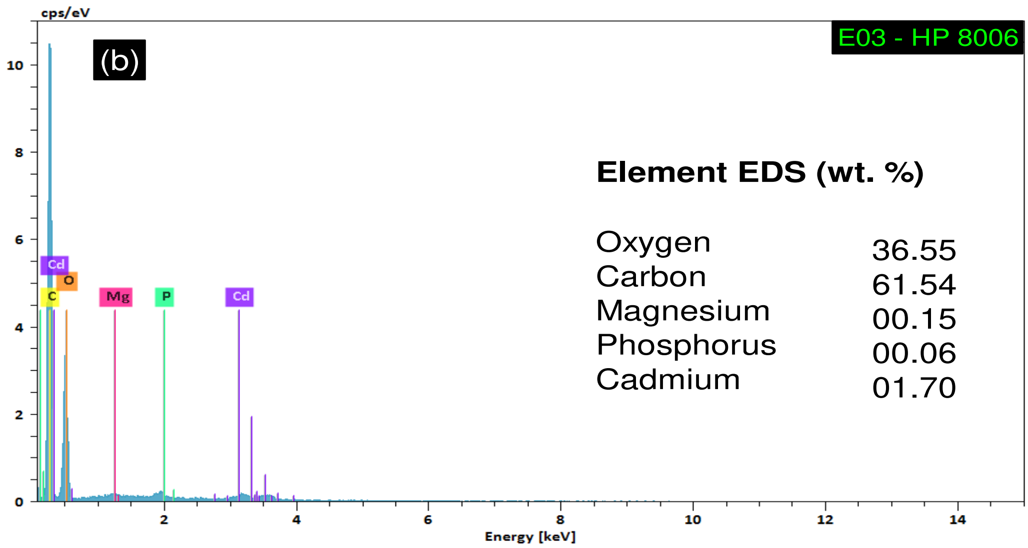


Fig. 10 SEM micrographs of MHFs





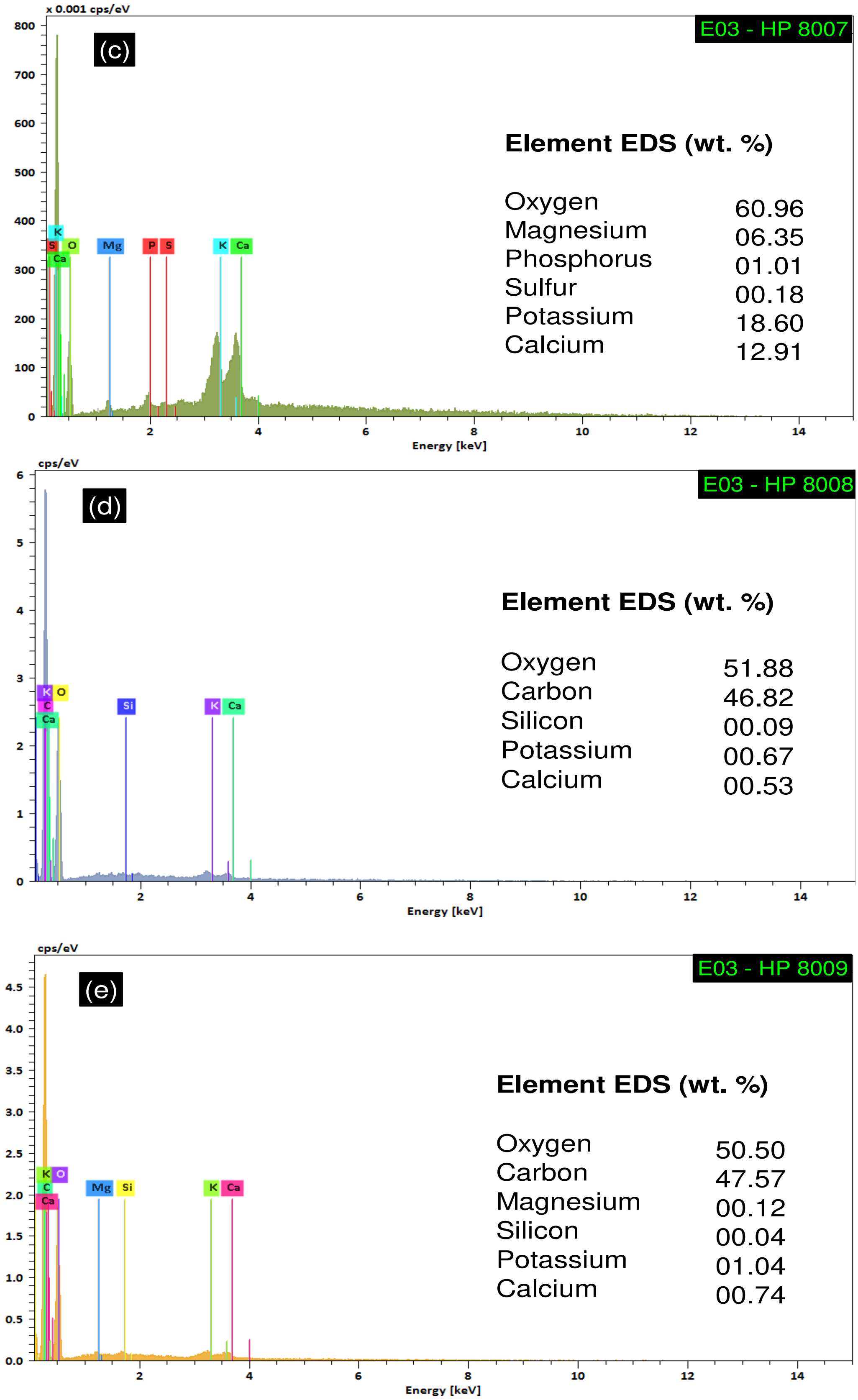


Fig. 11 (a) Selected areas for EDS; and (b-e) element analysis of the selected areas

Table 4. Mineralogical and elemental composition of MHFs

Crystallinity		Elemental Composition [mass norm. (%)]									
%Cr	CI	O	C	K	Ca	Mg	Cd	P	S	Si	Total
62.20	0.39	49.97	38.98	5.08	3.54	1.65	0.43	0.27	0.05	0.03	100.00

4.2 Density

Lightweight property of materials has become in recent years an essential criterion for reducing greenhouse gas emissions of the building sector and speeding up construction schedules. Indeed, the interest behind the development of low-density materials using bio-based fibers is that they can positively affect many properties of materials such as thermal (Liuzzi et al., 2018) and acoustic insulation (Binici et al., 2009). This section was devoted to evaluating the use of Moroccan hemp stems for the manufacture of lightweight plasterboards. Table 5 gives the average value of the density of hemp-plaster composites at dry state. As it can be noticed, the higher fiber content, the lower is the density. This decrease can be explained by the fact that hemp fibers act as a bio-pore-forming agent.

Fig. 12 illustrates the clear correlation between density decreases and fiber content. The results show that the apparent density of hemp-plaster composite MHP6 with 6% of hemp fibers was 1051 kg/m^3, resulting in a significant decrease of 24.5% compared to the reference case. Although these composites are suitable for use as a roof-ceiling compound, this interesting property requires further studies taking into account the mechanical behaviours in order to design optimum lightweight hemp-based composites for other building applications.

Table 5. Dry density variation of studied composites

Fiber content [%]	Density [kg/m^3]	
	Average	**SD**
0	1392	± 35
2	1235	± 37
4	1175	± 61
6	1051	± 74

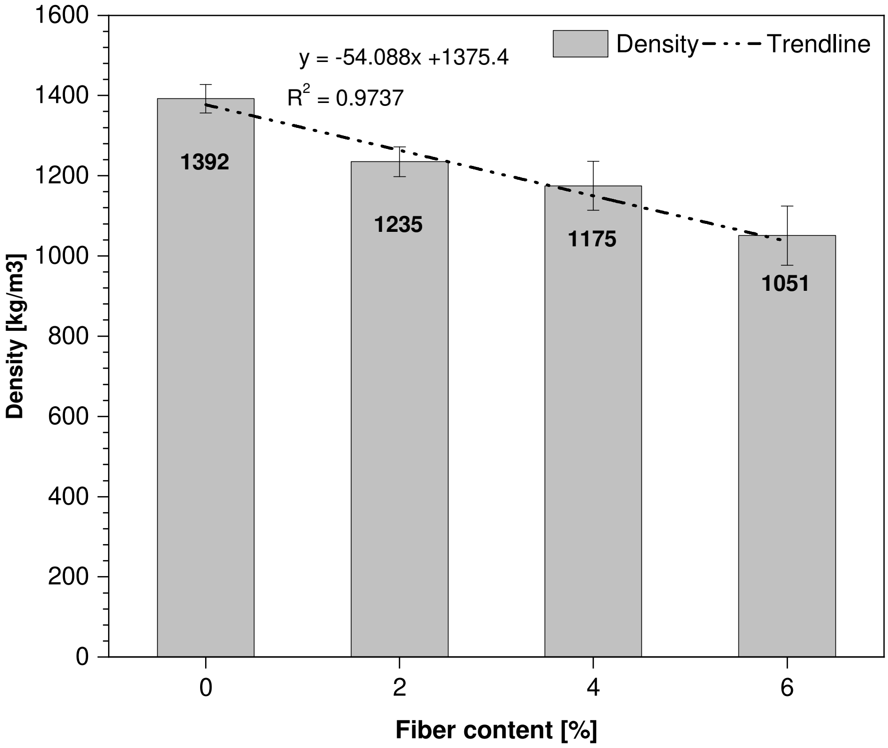


Fig. 12 Density versus fiber content

4.3 Thermal transport properties

The thermal transport properties of the developed MHP composites are given in Table 6.

It was found that the incorporation of MHFs into the plaster body improves the thermal insulation quality and reduces the thermal diffusivity. Consequently, the volumetric heat capacity and thermal effusivity were obviously decreased due to their proportionality with density. Fig. 13 illustrates the variation of thermal conductivity as a function of the density for the different composite mixtures, emphasizing the efficient use of Moroccan hemp stems for the manufacture of lightweight building compounds with high thermal insulation. The thermal conductivity of hemp-plasterboard, when compared with the reference plaster, decreased from 0.531 W/mK to 0.364 W/mK, representing a gain of 31.5% in the thermal resistance, and the thermal diffusivity decreased from 0.399 mm^2/s to 0.365 mm^2/s, representing a reduction of 8.5% in heat transfer rating. Besides, the volumetric heat capacity and the thermal effusivity were decreased by 24.8%, 28.3%, respectively.

Since the specific heat capacity c_p of building materials is fundamental for predicting thermal comfort level of buildings, the thermal capacity of developed plasterboards was discussed to evaluate their thermal performance at building scale. This thermophysical property was deduced using the well-known expression:

$$C_p = \lambda / (\rho\ a) \quad \text{(Eq. 5)}$$

Where λ is the thermal conductivity, ρ is the density and a is the thermal diffusivity of samples.

The results show that the specific heat capacity varies non-linearly with the addition of local hemp fibers. The incorporation of 2% by weight of fibers showed a maximum improvement of 4% in the thermal storage capacity compared to plaster without additives. The greater increase in thermal resistance, the larger heat storage, the slower heat transfer rating and the low-density of prepared hemp-plasterboards allowed to classify these bio-composites as thermally-intelligent lightweight building materials. The smart behaviour of local MHP composites can be observed in Fig. 14.

As above-mentioned, the heat transfer diffusion thought the different bio-composites was assessed by recording the temperature evolution of their irradiated upper side surface. The thermograms are given in Fig. 15. It appears clearly that the addition of MHFs in plaster slows the diffusion of heat, which can be very effective for thermal regulation purposes and passive building design.

This is confirmed by inspecting Table 7, where the time required to reach 1/3, 1/2, 2/3, and 5/6 of the maximum value of the temperature are presented. The values show that the higher fiber content, the lower is the rate of temperature spread through hemp-plasterboard composites and, consequently, the lower is the thermal diffusivity. For instance, the half of the maximum temperature is reached during t = 215 s and t = 262 s for the reference case and the MHP6 plasterboard, respectively. This may be explained by the heterogeneity characteristics of the composite mixture (Lachheb et al., 2019). By using Eq. 1, it was confirmed that the thermal diffusivity of plaster significantly decreases with the incorporation of MHFs.

In addition, the nonlinear variation of the thermal heat capacity of hemp-plasterboard composites shown in Fig. 14 is also asserted by the flash method tests presented in Table 7 where the time necessary for achieving maximum temperatures are deliberately indicated. Indeed, the thermal heat capacity characterizes the ability of building materials to store heat (Pezeshki et al., 2018). As a result, the higher is the heat capacity, the greater is the time necessary for increasing the temperature of a body. The results show that the slowest increase in temperature was for the addition of 2% in weight of MHFs. The time required to reach the maximum temperature was increased from t = 980 secs to t= 1000 secs, explaining the high thermal capacity of MHP2 compared to the reference case. Beyond 2% of MHFs, the maximum time decreases with the increase in MHF content. These results confirm the decrease of the thermal capacity of both MHP4 and MHP6 plasterboard composites shown in Fig. 14.

Table 6. Thermal transport properties of Moroccan hemp-plaster composites

Fiber content [%]	Th. Conductivity [W/mK]	Th. Diffusivity [mm^2/s]	Vol. specific heat [MJ/m^3K]	Th. Effusivity [$Ws^{1/2}/m^2K$]
0	0.531 ± 0.001	0.400 ± 0.011	1.327 ± 0.032	839 ± 09
2	0.485 ± 0.001	0.390 ± 0.008	1.243 ± 0.025	776 ± 07
4	0.441 ± 0.003	0.381 ± 0.019	1.159 ± 0.050	714 ± 13
6	0.364 ± 0.001	0.368 ± 0.003	0.990 ± 0.009	601 ± 03

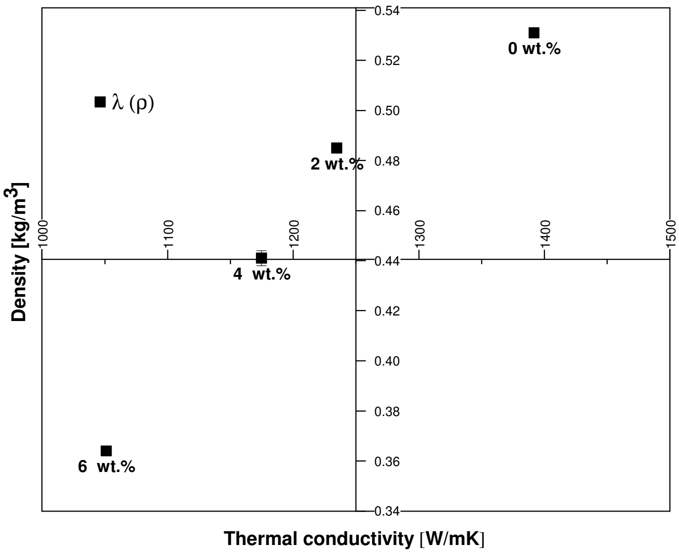


Fig. 13 Thermal conductivity versus density of hemp-plaster composites

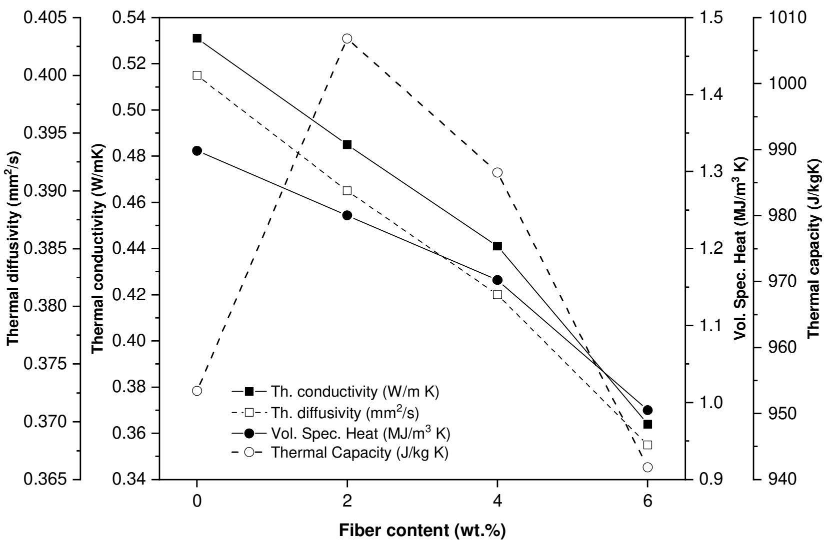


Fig. 14 Thermal properties of Moroccan hemp-plasterboards

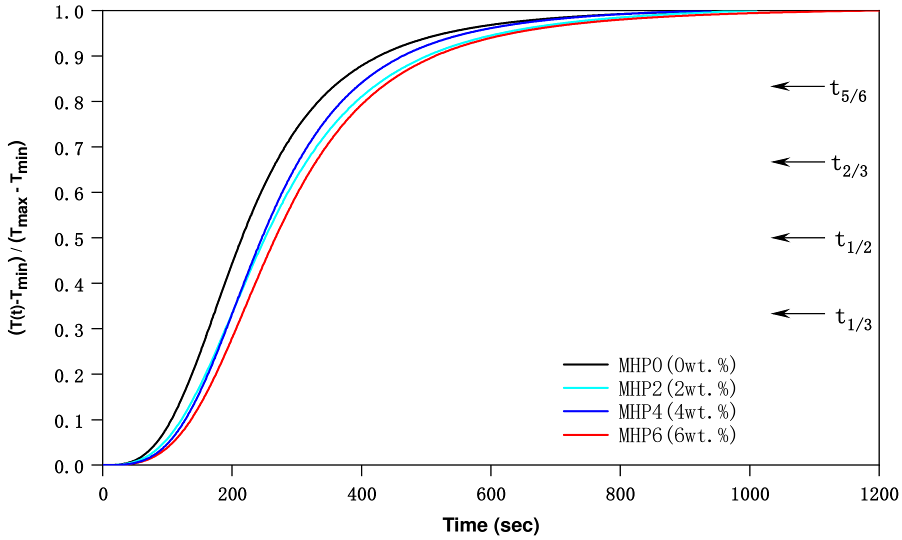


Fig. 15 Thermograms of the non-irradiated side of developed MHP composites

Table 7. Time needed to reach 1/3, 1/2, 2/3, 5/6 of the maximum temperature

Mixture code	Time				
	1/3	1/5	2/3	5/6	$t_{max} = t\ (T_{max})$
MHP0	173	215	267	358	980
MHP2	200	252	300	420	1000
MHP4	200	247	302	395	990
MHP6	210	262	327	434	940

4.4 Building simulation

4.4.1 Case study building

In order to evaluate the energy performance of the developed bio-plasterboards, the analysis of the energy consumption of a residential building with and without MHP composites under two different climates of Morocco was carried out. The case study building shown in Fig. 16 is an 80 m^2 single room facing north with a window-to-wall ratio of 20% and with the constructive characteristics listed in Table 8.

The building is chosen to be representative of typical Moroccan buildings with nationally commercial hollow bricks, which thermophysical properties were taken from Binayate prescriptive library developed by the Moroccan Agency for Energy Efficiency (AMEE, 2014). The thermophysical data of used building materials are given in Table 9. To assess the potential use of MHP plasterboards for passive cooling and heating of residential buildings in semi-arid climates, the building is assumed to be located in Oujda (34° 41' 12.001" N, 1° 54' 41" W) and Marrakech (31° 37' 48" N, 8° 0' 32" W), which are characterized respectively by cold and hot semi-arid climates. The effectiveness of the MHP plasterboards was compared through the total energy consumption as well as the annual building energy gain in both locations.

The thermodynamic behaviour of the building was simulated during a TMY using EnergyPlus software. Climate data of Oujda and Marrakech were provided by site-specific high-precision stations commonly used by ASHRAE for building design standards (ASHRAE, 2017a). More details about the used stations are presented by (Sghiouri et al., 2020).

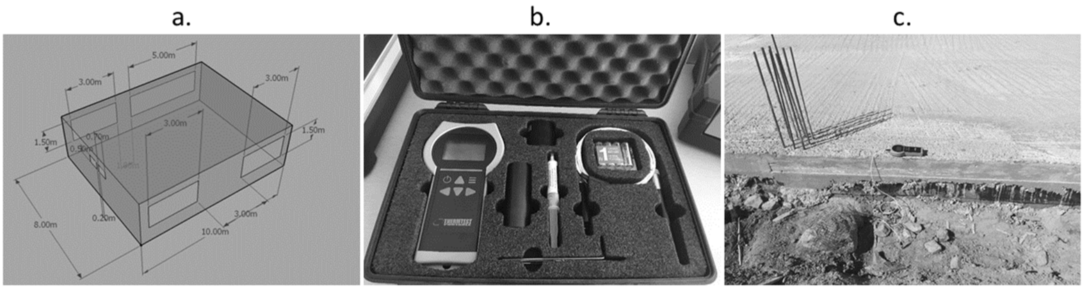


Fig. 16 Studied building: (a) 3D sketch plan (b) TLS-100 soil conductivity meter (c) Measuring place.

Table 8. Constructive characteristics of studied building (inside to outside)

Size	80 m^2 (10x8x3 m^3)
Layout	Monozone
Shape	Rectangular
Orientation	East-west
Exterior wall	Coating mortar (1.5 cm), hollow bricks (7 cm), air blade (10 cm), hollow bricks (7 cm) and coating mortar (1.5cm).
Roof	Hemp-plasterboard (5 cm), hollow-core slab (16 cm), reinforced concrete (5 cm), screed (5 cm) and tile (1 cm).
Floor	Tile (1 cm), screed (5 cm), reinforced concrete (20 cm) and soil layer (25 cm)
Glazing	Double glazed with PVC frame (U-value = 2.51 W/m^2K, G-value=0.44)

According to the U.S. Department of Energy (DOE, 2019), the use of undistributed ground temperatures given by the weather data can lead to very poor results, especially for the simulation of small residential buildings. To be closer to reality, we used in this study a portable soil thermal resistivity meter (TLS-100, Fig. 16b) to measure the thermal conductivity of soil under real slab conditions (Fig. 16c). The experimental results of the thermal conductivity and the thermal resistance of soil are given in Table 10. This value was entered as an input data into the EnergyPlus slab pre-processor to estimate the ground heat transfer of the case study building.

It should be noted that the simulations were carried out by only modifying the MHP plasterboards constituting the roof ceiling. The comparison between the performance of 40 mm tick MHP0 (reference case) and MHP6 plasterboards for building energy efficiency enhancement was examined.

Table 9. Thermal properties of materials used in the case study

Material	**Th. Conductivity (W/mK)**	**Density (kg/m^3)**	**Specific heat capacity (J/kgK)**	**Thermal resistance (m^2K/W)**
Coating mortar [a]	1.300	1900.0	1000	--
Hollow bricks [b]	0.203	990.0	729	--
Air gap [a]	--	--	--	0.180
Hollow-core slab [a]	1.039	3618.3	1000	--
Reinforced concrete [a]	2.500	2600.0	1000	--
Screed [a]	1.300	1900.0	1000	--
Tile [a]	1.300	2300.0	840	--
Soil layer [c]	--	--	--	0.251

[a] ASHRAE Handbook-Fundamentals (ASHRAE, 2017b); [b] Binayate library (AMEE, 2014) ; [c] Our work.

Table 10. Thermal resistivity of the case study building's soil

Test number	**Thermal Conductivity (W/mK)**	**Thermal Resistivity (mK/W)**
1	1.024	0.975
2	0.976	1.024
3	0.978	1.021
4	0.995	1.004
5	1.018	0.981
Mean	0.995	1.004
Deviation	0.022	0.022

4.4.2 Simulation results: Thermal loads and gains

In Fig. 17, the impact of the incorporation of MHFs on the annual energy needs of heating and cooling is presented. Although the small thickness of used hemp-plasterboards (40 mm), the results show clearly that the introduction of non-industrial hemp fibers into plaster reduces the annual energy consumption of buildings. It was found that the addition of 6 % in weight of MHFs has led to improving the building energy efficiency by decreasing the annual energy consumption from 92.1 kWh/m^2 to 87.8 kWh/m^2 for Oujda and from 82.1 kWh/m^2 to 77.7 kWh/m^2 for Marrakech, representing respectively a reduction of 4.7% and 5.4% of the total energy needs of the building. Besides the improvement of the thermal insulation of plaster, MHP composites demonstrate a significant impact on passive cooling, as shown in Fig. 18. This may be attributed to the increased time lag of the roof due to the great decrease in thermal diffusivity of developed MHP composites as previously presented in Fig. 15. These results demonstrate the potential use of local hemp-based plasterboards for passive cooling and the enhancement of the building energy efficiency in semi-arid climates.

In Morocco, the compliance of buildings is evaluated through Binayate prescriptive software, which is developed by the Moroccan Agency for Energy Efficiency (AMEE, 2014). For this reason, and to highlight the effectiveness of prepared Moroccan hemp-plasterboards (or CANNAPlasterboards) as commercial building materials for roof/ceiling applications, the ability of MHP composites to play a role in the construction of compliant roofs and meeting the Moroccan building thermal code (RTCM) is examined. Fig. 19 illustrates the composition of the studied roof composition which matches the model building's roof with the addition of a typical 30 mm XPS insulation material. In this study, the building materials are taken from Binayate prescriptive library, as given in Table 11.

Indeed, the roof compliance is assessed by calculating the thermal transmittance (U-value) of the building envelope using the following equation (AMEE, 2014):

$$U = 1/(1/h_i+1/h_e+\sum(e_i / \lambda_i) +\sum R_j) \quad \text{(Eq. 6)}$$

Where R_j is the thermal resistance of the j[th] layer, e and λ are respectively the thickness and the thermal conductivity of used building materials, $\frac{1}{h_i}+\frac{1}{h_e}$ represents the convective heat resistance of the building envelope on its inner and outer faces. For roofs, the convective heat resistance is equal to 0.22 m^2K/W according to (AMEE, 2014).

Table 12 represents the predicted U-value of the studied roof for each MHP mixture and shows clearly that the higher the fiber incorporation, the lower the u-value of the roof. Moreover, the results indicate that MHP6 acts as an auxiliary insulation building material that participates in meeting the thermal regulation requirements, demonstrating the effectiveness of incorporating MHFs into plaster for the manufacture of local high-performance plasterboards.

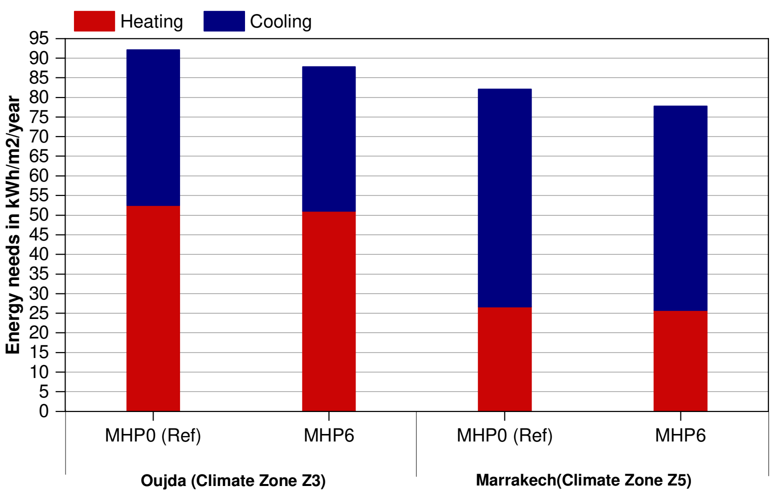


Fig. 17. Energy needs per unit total floor area (reference vs. 40 mm-tick MHP6 board)

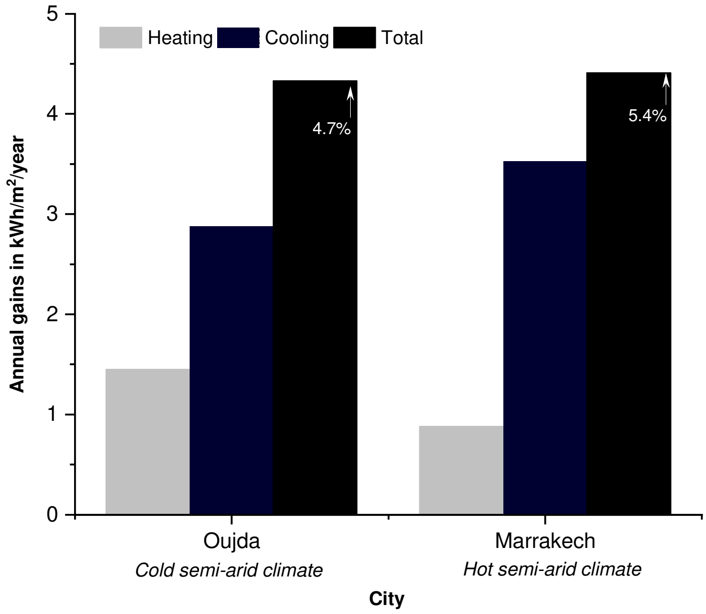


Fig. 18 Annual heat gain using 40 mm-tick MHP6 board

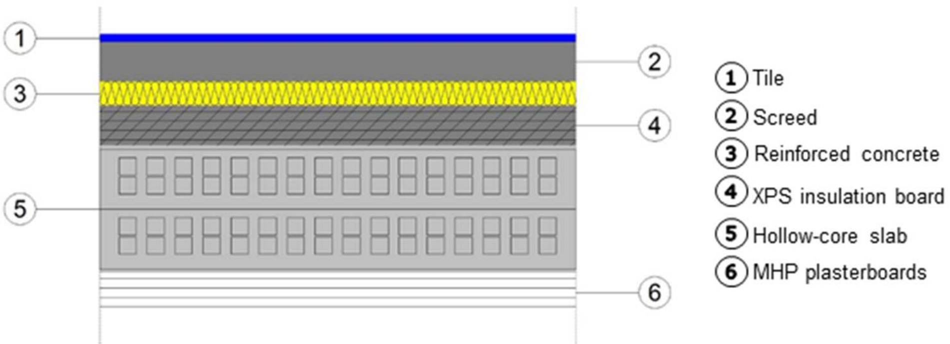


Fig. 19 Composition of the roof for RTCM compliant building

Table 11. Thermal properties of materials used in the RTCM roof (adapted to Binayate library (AMEE, 2014))

Material	**Th. Conductivity (W/m.K)**	**Density (kg/m^3)**	**Specific heat capacity (J/kg.K)**	**Thickness (cm)**
Tile	1.3	2300	840	1
Screed	1.3	1900	1000	5
Reinforced concrete	2.5	2600	1000	5
Hollow-core slab	1.039	3618	1000	16
Mineral wool	0.031	40	1000	3

Table 12. U-values of the roof with different MHP mixtures

Mixture code	U-value (W/m^{2}K)	Roof compliance RTCM ($\leq 0.650\ \mathrm{W}/m^2\mathrm{K}$)
MHP0	**0.666**	✗
MHP2	**0.662**	✗
MHP4	**0.651**	✗
MHP6	**0.647**	✓

4.5 Discussion

The experimental and simulation findings show the potential use of non-industrial hemp in plaster to develop effective building materials for passive thermal comfort in semi-arid areas. Moreover, the study shows that the locally developed bio-based plasterboards possess interesting thermophysical features and can serve as auxiliary insulation materials for retrofit and participate in upgrading the thermal performance of building envelopes to meet the thermal regulation standard of Moroccan buildings.

In comparison to the experimental study conducted in (Lachheb et al., 2019) on the incorporation of spent coffee grounds in Moroccan plaster, which shows good results for passive heating, the hemp/plaster mixture shows best results in passive cooling. This is explained by the high thermal inertia of hemp-based building materials (Dhakal et al., 2017).

Although the present study reveals promising results, there is a lack of information about the use of non-industrial hemp fibers in buildings. This green building material may also enhance the indoor air quality of buildings (Le et al., 2010).Thus, further building-scale studies are needed to assess the mechanical and hygrothermal properties of non-industrial hemp composites.

5 Conclusion

This paper deals with the valorization of vernacular hemp in building materials manufacturing by investigating the effect of fiber addition on the thermal insulation of plaster. Firstly, the microstructure, mineralogical and chemical composition of Moroccan hemp stems were investigated using X-ray diffraction (XRD), thermal gravimetric analyses (TGA), scanning electronic microscopy (SEM) coupled with energy dispersive spectroscopy (EDS). It was established that the microstructure of non-industrial hemp of Morocco was quite similar to the industrial one and has interesting properties for insulation material applications owing to its porous structure and its good percentage of crystallinity, which was found equal to 62.25%. Four local bio-composites made of plaster and different percentage addition of Moroccan Hemp Fibers (MHFs) were developed and characterized to assess the thermal impact of fiber addition on plaster-based materials. All thermal transport properties of studied mixtures were simultaneously measured by means of the hot disk method. The variation of the thermal heat capacity of samples was also discussed and confirmed using the flash method. Experimental tests have shown that the incorporation of Moroccan hemp fibers leads to a linear decrease in density and enhances the thermal insulation quality of plaster. This means a smart behaviour of the mixture in designing lightweight roof structures with high thermal resistance. The addition of 6% in weight of MHFs decreased the thermal conductivity of plaster from 0.53 W/mK to 0.36 W/mK, and the thermal diffusivity from 0.399 mm^2/s to 0.365 mm^2/s, highlighting the potential use of Moroccan hemp stems as a partial replacement in plaster-based building materials for passively improving the indoor thermal comfort level and the energy efficiency of popular constructions, especially in rural areas of Morocco. The simulation results of a typical Moroccan building located in a cold (Oujda) and hot (Marrakech) semi-arid climate indicate that, compared to conventional ceiling composition, roofs with 40 mm hemp plasterboard are able to participate in meeting the thermal regulatory requirements and reduce the thickness of the required insulation board, thus reducing the annual energy consumption of the buildings (reduction of more than 4.7%). Hence, Moroccan non-industrial hemp fibres can be a good alternative as a partial replacement of plaster for the manufacture of high-performance bio-insulating plasterboards.

Acknowledgment

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Conflicts of interest

None.

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